Global Positioning System Timing Receivers in the DSN

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The Global Positioning System (GPS) is a worldwide navigation system using a constellation of earth satellites with onboard clocks. The GPS is also usable to transfer time and frequency. JPL has provided part of the funding to the National Bureau of Standards (NBS) to build GPS timing receivers. Preliminary tests with the breadboard receiver at NBS has produced remarkable precision in time and frequency transfer between the United States Naval Observatory (USNO) and NBS. JPL plans to install receivers in the DSN to demonstrate their ability to transfer time and frequency within the DSN and between the DSN and outside agencies.

I. Introduction

JPL is procuring two Global Positioning System (GPS) satellite timing receivers from the National Bureau of Standards (NBS). JPL has funded a large part of the development of the receiver design at NBS. The GPS timing receivers are to be evaluated for use in the DSN as a method of time and frequency transfer among the stations of the DSN, and between the DSN and world time and frequency standards.

JPL plans to demonstrate the use of a GPS timing receiver system as a method of significantly reducing the cost of meeting the functional requirements for time and frequency transfer.

II. The Global Positioning System

The GPS is a Department of Defense worldwide navigation system that uses a constellation of orbiting Earth satellites, each of which carries an onboard clock (Ref. 1). Stored on each space vehicle (SV) is information on its position with respect to an Earth-based rectilinear coordinate system. If this time and position data were transmitted to an Earth-based station with its own clock, then the difference in time, neglecting relativistic effects, would be the propagation delay of the signal. Hence the observer can determine his position as being somewhere on a sphere which has its center at the spacecraft. By viewing three SVs and by having a reasonably good clock, an observer can determine his position exactly. By viewing four SVs, the observer can determine his position using a poor clock.

The GPS satellite configuration calls for 24 SVs. This number has been reduced to 18 due to budgetary considerations. The SVs are distributed in three orbital planes inclined 63° with respect to the Earth's equatorial plane, and offset from each other by 120° longitude. Each SV is in 12-hour prograde orbit. This distribution is meant to maximize the number of SVs visible to an observer anywhere on the earth at any time.

The GPS SV signal is at two frequencies: link 1 at 1575.42 MHz and link 2 at 1227.6 MHz. These frequencies are multiples of 10.23 MHz, namely:

$$\text{link } 1 = 1575.42 \text{ MHz} = 10.23 \text{ MHz} \times 154$$

$$\text{link } 2 = 1227.6 \text{ MHz} = 10.23 \text{ MHz} \times 120.$$

This is a particularly good frequency region for a couple of reasons. First, there is little use at these frequencies, so it is relatively easy to obtain an allocation. Second, the effects of the ionosphere on the propagation delay are smaller than at lower frequencies.

The GPS SV transmits two PN codes on link 1; they are named the P code and the C/A code. The GPS timing receiver uses only the C/A code. The C/A code is 1023 bits long and is transmitted at a 1023-Mbps rate; hence its duration is 1 ms. Each SV's code is unique so that all the SVs can use the same RF carrier frequency and yet a receiver can pick out a particular SV's signal. The data are transmitted at a 50-bps rate, so there are 20 C/A code sequences for each data bit. The data consist of 4 blocks. Data Block 1 contains the clock corrections for the SV clock with respect to GPS time. Data Block 2 contains ephemeris information for that particular SV. There is a message block that contains any messages that might be needed. Finally Data Block 3 contains an almanac of the locations of all of the SVs in the GPS constellation. The complete message takes 6 seconds to transmit.

III. Description of the Receiver

The NBS GPS timing receiver system consists of three chassis which are rack-mountable and a separate low-noise amplifier and down-converter which are mounted at the antenna. The rack-mountable chassis take a combined vertical rack space of about 18 inches, a keyboard which takes about 4 inches more and a printer which takes about 6 inches.

A 100-MHz local oscillator frequency is sent to the antenna-mounted down-converter. This signal is subsequently multiplied (×15) and mixed with a 1.57542 GHz out of the wide band front end amplifier to produce a 75.42 MHz IF frequency.

The balance of the receiver is what is known as a Tau Dither Delay Lock Receiver (Ref. 1). The receiver has two loops. The inner loop is a delay lock loop. Its function is to lock to the incoming PN code, thereby producing a signal the outer phase lock loop can lock to.

The receiver must perform a cross correlation operation to extract a signal from a particular SV. To do this, the PN code of the particular SV is replicated in the receiver. Then the replicated code is shifted (delayed) until a correlation is found. With correlation, the receiver locks to the code with the delay lock loop and to the signal with a phase lock loop.

IV. Timing and Frequency Transfer

A. Synchronization

One fundamental aspect of time is that of simultaneity.[1] A definition given by NBS for simultaneity is: "Two events are simultaneous if equivalent signals, propagating in a given media, arrive coincidentally at a common point in space which is geometrically an equal distance from the source of each event. In practice a much broader definition is often used for clock synchronization; i.e., two clocks have the same reading in a specific reference frame" (Ref. 2).

If two clocks are beating simultaneously, in a specific reference frame, they are said to be synchronized. All of us have synchronized one clock to another by setting our wristwatch to the mantel clock. We make the time reading (date) of one clock agree with the date of another clock.

If clocks are located some distance from one another, the problems of accurate synchronization become difficult. Of course we use radios and telephones to get the date, but these methods are not usable to transfer the date with an accuracy of microseconds or nanoseconds.

Early in the 17th century Galileo devised a method of date transfer using observations of the moons of Jupiter. The Jovian satellite system is a clock that is observable from any place on the Earth. All one needed was an ephemeris table and a reasonable telescope and he could synchronize any clock on Earth. This is an application of the first definition of simultaneity. Note that every place on Earth is approximately the same distance to Jupiter. This technique was used extensively for over 100 years for map-making; however, it was not usable on ships at sea because of the difficulty of looking through a telescope from a pitching deck.

With good portable cesium clocks the definition of synchronization of widely separated clocks is a "clock trip" from one clock to the other, then back to the first clock. This is called a clock closure. This method invokes the second definition of synchronization. The most careful clock trips take into account the path of the traveling clock to correct for relativistic effects and refer the clocks to the same reference frame

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[1]There are three aspects of time: time interval, date (the clock reading), and simultaneity.

(Ref. 3). This is one of the methods presently used in the DSN.[2]

Over the last several years people have been getting back to Galileo's method of using satellites for time transfer. For example NBS has been using the GOES weather satellites for time transfer. The DSN has used a technique of bouncing timing pulses off the Moon. Now both NBS and the United States Naval Observatory (USNO) are using the GPS satellites for time transfer.

The GPS can be used in several ways to accurately transfer time between two or more known locations on the Earth. I shall describe two methods which are planned during the JPL/NBS demonstration.

The first of these two methods is a simultaneous common view (mutual view) of a single GPS satellite. With this technique the common mode ephemeris errors cancel, and the satellite clock error contributes nothing. If the two or more clocks are within 3000 km of each other so that the observation angles are high, one can expect a measurement accuracy of 10 nanoseconds time difference between the observers' clocks. If the propagation and ephemeris errors can be reduced, the accuracy can be reduced to 1 nanosecond.

The specific procedure for a mutual view observation is quite simple. The observers agree to observe a given satellite at a given time. Alernatively, if an observer knows another's observation schedule, he only has to make his schedule agree with the other's. The data of a complete observation of a satellite would include the date of the observation to the second and the time offset from the observer's clock to the GPS clock. At some time later the observers can exchange data.

Ideally an observatory's daily observation schedule would be on sidereal time.[3] This would mean that the SV would appear in the same position in the sky every day at observation time. The advantage of this method is the elimination of variables associated with direction. As the two clocks are separated, the angles of mutual view of the satellites become more shallow. As this happens, the ephemeris and propagation errors become larger, so the measuring accuracy is decreased.

[2]In addition to clock closures, VLBI methods are now being used between the DSN stations. In Spain the Loran-C navigation system is used and in Australia television synchronization signals are used to transfer time.

[3]Sidereal time is the time used by astronomers. It uses observations on the fixed stars rather than the Sun. A sidereal day is about 4 minutes shorter than a mean solar day; hence the time of observation would advance about 4 minutes per day mean solar time.

The second method is to make successive observations of the same SV clock (sequential view). The first observer synchronizes his clock with the SV clock when the SV is at a good viewing angle. A second observer then synchronizes his clock to the same SV at some time which is less than 12 hours later than the first observation, and when the SV is at a good viewing angle for him. If the SV that is observed has a cesium clock, then the date uncertainty will be about 5 ns over a 12-hour period. The ephemeris errors will tend to cancel because the same SV is used.

As in the case of portable clock trips, the relativisitic effect needs to be taken into account for a precision time transfer (Ref. 3).

B. Syntonization

Closely related to synchronization is the concept of syntonization. Syntonization is the act of putting two oscillators on the same frequency (tone). It is a musical term and is found in some dictionaries so defined. The term syntonization accuracy refers to a number $(f - f_0)/f_0 = \Delta f/f$, which is a measure of how close the frequency of one oscillator is to that of another, where f_0 is the frequency of the reference oscillator and f is the frequency of the measured oscillator.

As presently conceived, the operation of the GPS receiver would be used to take a reading of time offset once a day between two clocks. If clock A's oscillator is running fast with respect to clock B's oscillator, then clock A's value of date will advance with respect to clock B's value of date. Therefore, by taking daily clock offset readings one can determine the difference in rates between the two clocks oscillators, given $\Delta f/f$.

V. Present Performance of the Receivers

At present NBS and USNO are conducting daily mutual view observations of SVs. This means that NBS acquires and receives data from the same SV at the same time USNO is doing so. NBS is using a breadboard version of a receiver of NBS design. USNO is using a receiver purchased from Stanford Telecommunications Incorporated (STI).

USNO observes five SVs daily. The offsets between GPS time and USNO Master Clock (MC) are published weekly in a USNO Bulletin (Fig. 1). In addition, the data are available daily by telephone using a MODEM and a terminal. The data consist of the offset in nanoseconds between GPS time calculated by each satellite and the time of the MC. Also the data includes the date to the second that the data were taken.

The USNO measures the offset between GPS time and MC. The MC is the physical realization of UTC (USNO)[4] and is designated UTC (USNO, MC). Because of the present method of steering the MC, the time scale UTC (USNO, MC) differs from UTC (USNO) by some small amount (several nanoseconds). This offset is available on the telephone on a daily basis in the same way as the GPS data.

NBS observes four SVs daily, scheduled so that it has a mutual view of USNO. The SVs are SV-5 and SV-9, which have cesium clocks on board, and SV-6 and SV-8 which have rubidium clocks. NBS measures the offset between GPS time by each SV and NBS clock 9 [(UTC (NBS, CL9))].

In the same way, UTC (USNO, MC) has some offset from UTC (USNO), UTC (NBS, C19) as some small offset from UTC (NBS). These data are not published but are available from NBS.

There is a bit of a scheduling problem in the mutual view exercise between NBS and USNO. The NBS receiver corrects its viewing time 4 minutes a day to make up the difference between mean solar time and sidereal time. The USNO receiver on the other hand is corrected 28 minutes once a week. This means there is a slight departure from sidereal time as the week wears on. I understand that USNO will eventually operate the receiver on sidereal time. At the present NBS has to change the schedule every day.

The big advantage of viewing the SV on a sidereal schedule is that it will appear in the same position in the sky every day. This is important if there are any multipath problems and with respect to syntonization. To measure frequency offset, the important thing is change in time. If we look at the SV in the same place in the sky every day, a lot of variables cancel.

Present measurements between USNO and NBS have shown that the short-term characteristics of the GPS signal have white noise phase modulation (white PM) as a limiting noise process. The method of determining this was a new technique called the Modified Allan Variance (mod $\sigma^2 y(\tau)$). Mod $\sigma^2 y(\tau)$ as its name implies is a modification of the traditional method of characterizing frequency stability, the Allan Variance. Using mod $\sigma^2(\tau)$, one can easily distinguish between white PM and flicker phase noise (Flicker PM). Flicker PM is a type of power spectral density which is inversely proportional to the spectral frequency $\omega/2\pi$. If Flicker PM noise is present then there is a logarithmic divergence of the standard deviation which increases with the number of samples taken (Ref. 4). So it is important to determine if this noise process is present.

Knowing the limiting noise process to be white PM, one can safely proceed using the statistics of the normal distribution. The results of this analysis have shown that one can measure time differences to less than one nanosecond for averaging times of 4 minutes (Ref. 5). The data from the two receivers are being analyzed by both NBS and JPL. Results have been published by NBS (Ref. 7). Figure 2 is a graph of UTC (USNO) – UTC (NBS) versus days. The graph covers about a four-month period. During this period several clock trips were made between USNO and NBS. The agreement is shown on the graph.[5]

The syntonization between the rates of UTC (USNO) and UTC (NBS) can be measured using the GPS timing receivers. If a set of time difference measurements are made using a single SV, then a slope can be found of time difference versus time, by finding a least square linear fit to the data. This assumes that the noise causing the variations in readings is white. This procedure is repeated for several SVs which produces a set of slopes (Fig. 3a,b,c,d). The slopes are a measure in the difference in rates of the two clocks as measured by using different SVs.

A second assumption is now made; that is, the measures of these slopes are independent. Next, the mean and standard deviation and the standard deviation of the mean are found for the set of slopes.

For the period 5 Sept 81 to 16 Sept 81[6] the slopes of [UTC (USNO)] – [UTC (NBS)] by the several SVs are:

by SV 5 –11.32 nanosec/day

by SV 9 –11.35 nanosec/day

by SV 6 –10.73 nanosec/day

by SV 8 –11.87 nanosec/day

The mean is	–11.07 nsec/day
The standard deviation is	–0.67 nsec/day
The standard deviation of the mean is	–0.33 nsec/day

[4]UTC universal coordinated time. The new UTC was adopted by the International Radio Consultive Committee (CCIR) in 1971 and put into effect 1 Jan. 1972. In this system all clocks run at the same rate, based on an atomic cesium clock.

[5]The measurement of the time offset via GPS has an offset of +445 nanosec with respect to the clock closure. The reason is unknown at this time; it is probably due to design differences in the USNO and NBS receivers. The offset was removed from the GPS data.

[6]These dates are arbitrarily taken. The period happens to be a set of continuous data. Other sets have produced better results.

The standard deviation of the mean is found by

$$\frac{SD}{\sqrt{N}} = \frac{0.67}{\sqrt{4}} = -0.33 \text{ nsec/day}$$

where SD is the standard deviation and N is the number of degrees of freedom. Since it was assumed that the measurements via the different SVs were independent, this number is 4, the number of SVs.

The value of 0.33 nanosecond per day corresponds to

$$\frac{0.33 \times 10^{-9} \text{ sec/day}}{86{,}400 \text{ sec/day}} = -3.82 \times 10^{-15} \frac{\Delta f}{f}$$

which is a measure of syntonization.

VI. The GPS Timing Receivers in the DSN

The GPS timing receivers will be deployed in the DSN in several steps. The first step will be to establish time and frequency transfer between NBS and the Time Standard Ensemble located at Goldstone. The final step will be to establish time and frequency transfer throughout the DSN.

The first step of the demonstration will be to install the two GPS receivers at the Goldstone clock ensemble at Goldstone. The receivers will be scheduled to perform mutual view observations with NBS and USNO.

This configuration and procedure will repeat the demonstration that is presently being performed between NBS and USNO. There will be a receiver at each of these two clock ensembles. The ensembles are located some distance from each other but not so great a distance that the mutual viewing angles are shallow. Finally there is a regular traveling clock trip between these clock ensembles. This demonstration will not only confirm the NBS-USNO experiment, but it will establish a time and frequency transfer between the DSN and NBS. The immediate results of this configuration and procedure will be to reduce the necessity of clock trips between the Goldstone clock ensemble and NBS from every 120 days to once a year or even less often. It is planned to permanently have one of the receivers at the Goldstone clock ensemble. Therefore this saving can be continually realized.

Another saving will be realized when the Goldstone clock ensemble is moved to DSS 14. This move is planned for sometime in 1983. The presence of a GPS receiver will greatly help maintain time and frequency during the move.

The reason for placing two GPS receivers at the same place is to check the receivers themselves and act as a control for the Goldstone-NBS experiment. The two receivers should give identical results if their antennas are in the same location. In addition this will give us a chance to check the receiver before it is sent to another station in the DSN.

I plan to repeat the procedures that are now being done between NBS and USNO. The difference is time and frequency transfer from NBS to the Goldstone clock ensemble rather than USNO. In addition time comparisons will be made between the two GPS receivers which are located next to one another at the Goldstone clock ensemble. These measurements should be identical except for any errors in the receivers themselves.

Beyond repeating the NBS to USNO demonstration and the establishment of time and frequency transfer from NBS to the Goldstone clock ensemble, an even more informative measurement will be available. If the NBS, USNO and the Goldstone clock ensemble GPS receivers are all on the same schedule, for mutual view, then a three-station measurement closure will be available. This will be somewhat akin to the three baseline VLBI closures reported in Ref. 8 except that all of the stations will be located in the continental U.S.

This will allow a simultaneous measurement of the time offset [UTC (USNO) – UTC (DSN)], [UTC (USNO) – UTC (NBS)] and [UTC (USNO) – UTC (DSN)]. There will be two checks of the accuracy of time transfer using the GPS receivers. First the offsets [UTC (USNO) – UTC (NBS)] and [UTC (NBS) – UTC (DSN)] are well-known and kept with traveling clocks.[7] Second, by the closure measurement it should be possible to get a measure of the absolute accuracy of the GPS receiver system independent of clock trips.

The second step will be to move one of the GPS timing receivers to DSS 63 in Spain. Spain was chosen as the second installation because it is closer to Goldstone GTS than DSS 43 in Australia. The great circle distance between GTS and Madrid is approximately 85° whereas the great circle distance between Goldstone and Canberra is approximately 110°.

It is also possible to complete a closure of measurements which includes DSS 63. USNO is approximately 55° great

[7]All times have been subtracted from UTC (USNO). This corresponds to using USNO as the Standard. This is done for convenience. JPL traditionally uses NBS as the Standard for the DSN because of its proximity.

circle distance from Madrid. There will be mutual view measurements (once per day, it is hoped) among the four locations USNO, NBS, Goldstone and DSS 63. This daily mutual view might involve some low viewing angles from DSS 63 because of nonconformance to USNO's schedule. Daily mutual or sequential view between Goldstone and DSS 63, which is independent of outside agencies, is being planned.

There are plans by NBS to install a receiver in Paris, France, at the Bureau International de l'Heure (BIH), sometime in 1982. Paris is only 10° great circle distance from Madrid; therefore one could expect the same performance as between USNO and NBS. This assumes a daily high angle observation from BIH.

The third step will be to install a receiver at DSS 43. This is the most difficult step because of the distance. The great circle distance from GTS to DSS 43 is approximately 110° and from DSS 43 to DSS 63 approximately 160°. Mutual views at these distances are right above the horizon; therefore a schedule of sequential views will probably be the more useful. Because JPL will have only two receivers we are planning to use one of NBS's receivers for the DSS 43 demonstration.

An exciting experiment will be a three-station closure of DSS 43, DSS 63 and GTS. The results of this will be compared to the VLBI three station closure in 1979 (Ref. 7). The DSN receivers will be scheduled to make a three-station closure every day if possible. Certainly we will make an offset measurement, [UTC (DSN) – UTC (DSS 43)] and [UTC (DSN) – UTC (DSS 63)], every day.

VII. Conclusion

It is no mean task to determine the accuracy of time transfer over intercontinental distances using the GPS receivers. Suppose a sequential view of a SV is taken by two receivers anyplace on the Earth. Furthermore, suppose the SV is equipped with a çesium clock. Then time transfer accuracies of 10 nsec to 50 nsec are anticipated (Ref. 8). This means for a three-station closure the expected error is $\sqrt{3}$ times the individual experiment error or, 17 – 86 nsec. By using multireceiver closures, and repeating the short distance (<4000 km), transfers which were demonstrated in the continental U.S., the accuracies can certainly be confirmed.

The obvious way to determine the accuracy of GPS receiver time transfer is to make an independent measurement using established methods. Data on the regular clock closures give errors of 300 nsec, which is too large to measure GPS receiver performance. A careful clock closure could yield an error of 35 nsec for a trip of <40 hours each way, with three such trips 2 months apart. Frequency could be measured with an error of $1 \times 10^{-14}\ \Delta f/f$.

The other method of time transfer used in the DSN is VLB1. Present VLB1 errors are approximately 100 nsec from DSS 14 to DSS 63, and 200 nsec from DSS 14 to DSS 43. The DSS 43 to DSS 63 baseline measurement is not done often but the accuracy of that baseline is approximately 300 nsec. Within the next few months, there are plans to implement new techniques that are expected to decrease the errors from one to two orders of magnitude (Refs. 9, 10). This would mean that VLB1 could be used as an independent measurement of the time offsets between the clocks in the DSN.

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GLOBAL POSITIONING SYSTEM (GPS)

VALUES PRESENTED BELOW FOR NAVSTAR GPS SATELLITES ARE THE RESULT OF A LINEAR FIT THROUGH APPROXIMATELY 100 DATA POINTS, REFERRED TO THE BEGINNING OF THE TRACKING PERIOD (TIME OF MEASUREMENT). SATELLITES ARE TRACKED FOR APPROXIMATELY TEN MINUTES.

		NAVSTAR 1 SV# 4	NAVSTAR 3 SV# 6	NAVSTAR 4 SV# 8	NAVSTAR 5 SV# 5	NAVSTAR 6 SV# 9
	MJD	MC-GPS UT	MC-GPS UT	MC-GPS UT	MC-GPS UT	MC-GPS UT
NOV. 9	44917*	-	-	-	-	-
10	44918	-49.805(180448)	-49.877(175330)	-49.879(174224)	-49.866(191530)	-49.867(190530)
11	44919	-49.697(180430)	-49.805(175330)	-49.811(174230)	-49.798(191548)	-49.792(190430)
12	44920	-49.705(180442)	-49.743(175354)	-49.755(174230)	-49.737(191548)	-49.732(190430)
13	44921	-49.621(180448)	-49.677(175330)	-49.688(174230)	-49.673(191554)	-49.676(190448)
14	44922	-49.538(180430)	-49.592(175330)	-49.607(174230)	-49.599(191530)	-49.595(190430)
15	44923	-49.419(180424)	-49.544(175400)	-49.545(174218)	-49.534(191548)	-49.546(190424)
16	44924	-49.434(180454)	-49.475(175348)	-49.480(174218)	-49.472(184830)	-49.458(183818)
17	44925	-49.306(173730)	-49.404(172630)	-49.412(171518)	-49.381(184830)	-49.398(183730)
18	44926	-49.253(173730)	-49.352(172654)	-49.353(171530)	-49.775(184830)	-49.012(183730)

*NO DATA DUE TO RECEIVER MALFUNCTION

Fig. 1. Time differences between USNO master clock minus GPS time (from a U.S. Naval Observatory publication)

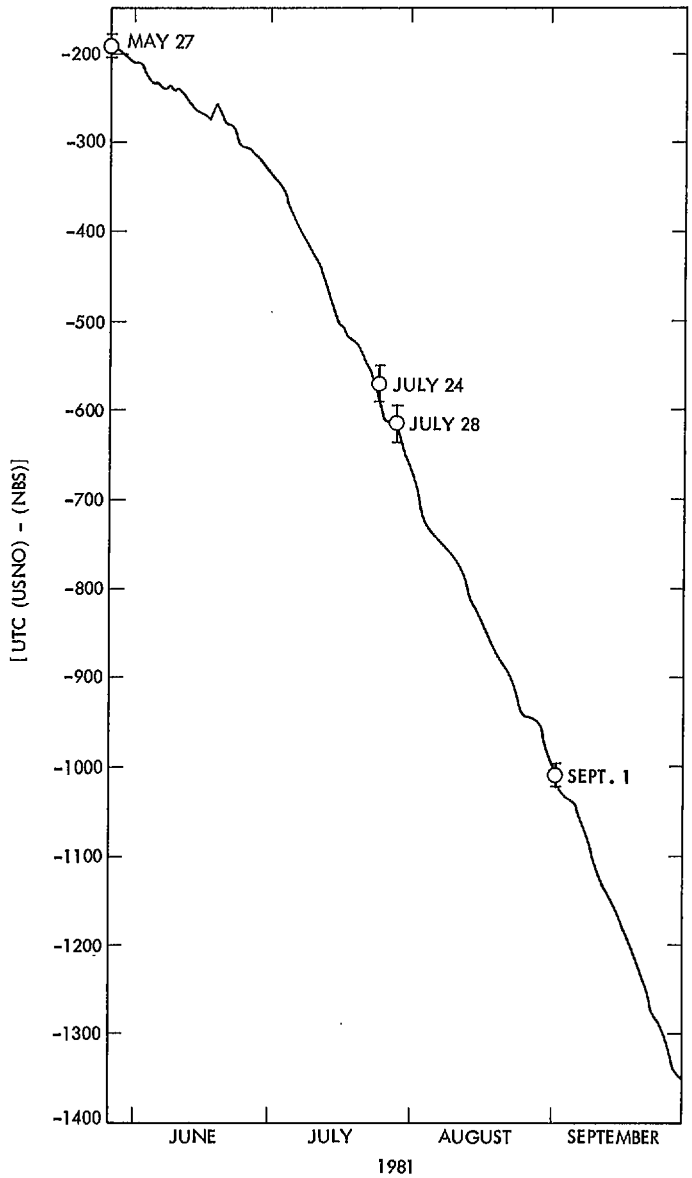

Fig. 2. UTC (USNO) minus UTC (NBS) vs time

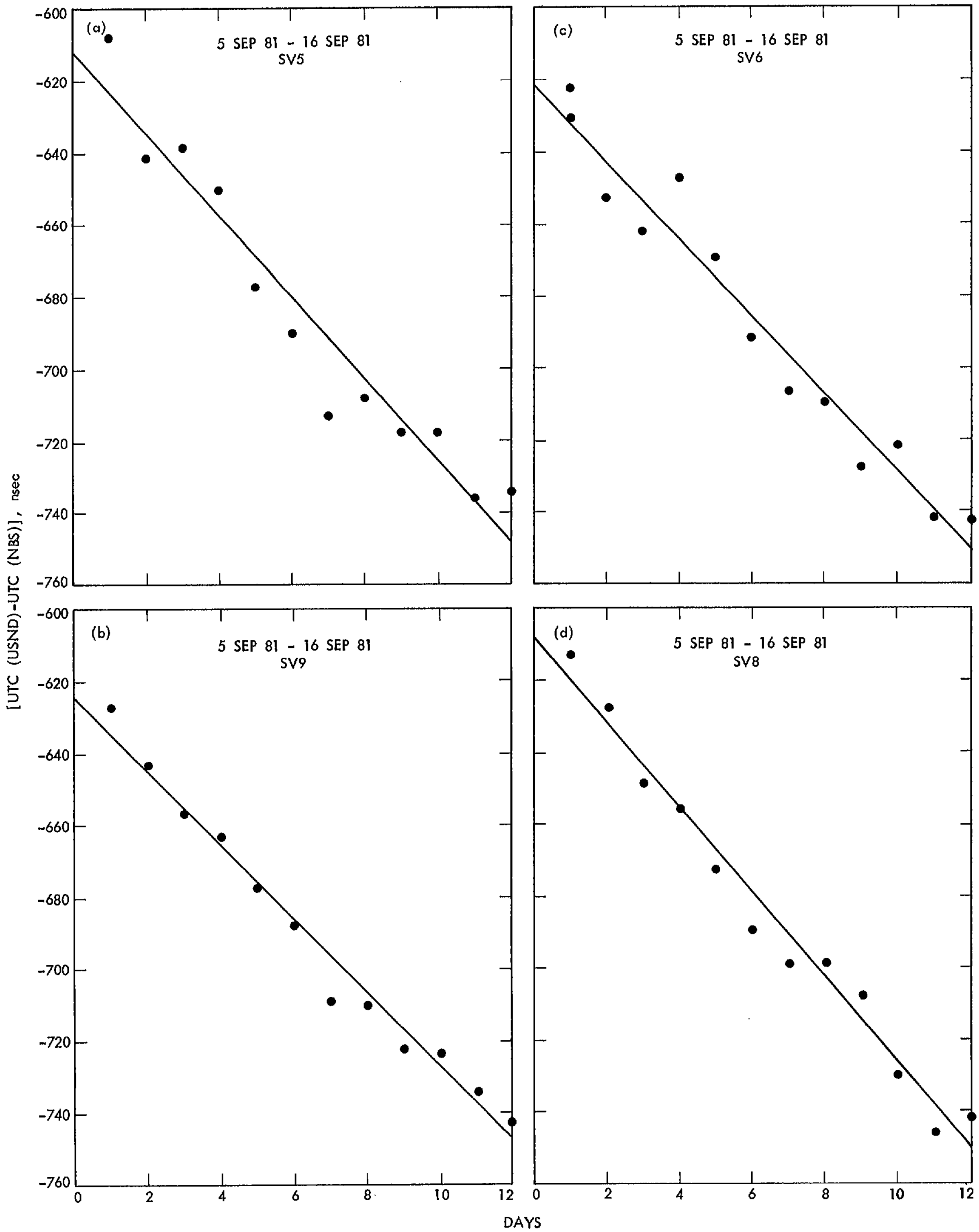

Fig. 3. UTC (USNO) minus UTC (NBS) vs time for four SVs